CALIFORNIA INSTITUTE OF TECHNOLOGY

EARTHQUAKE ENGINEERING RESEARCH LABORATORY

AMBIENT VIBRATION TEST OF A THIRTY-NINE STORY STEEL FRAME BUILDING

BY

MIHAILO D. TRIFUNAC

EERL 70-02

A REPORT ON RESEARCH CONDUCTED UNDER A GRANT FROM THE NATIONAL SCIENCE FOUNDATION

PASADENA, CALIFORNIA

JULY 1970

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INTRODUCTION

In recent years a method of structural testing based on wind and microtremor induced vibrations has been developed. Although in principle the method has been in use by the United States Coast and Geodetic Survey (United States Coast and Geodetic Survey, 1936) for almost forty years to measure fundamental periods of buildings, it was not until recently that this approach has been extended to higher modes (Crawford and Ward, 1964; Ward and Crawford, 1966; Blanford et al., 1968; McLamore, 1970; Trifunac, 1970).

This method has the advantages that it requires only relatively short and simple field measurements, it does not interfere with normal building function and the measuring instruments and equipment can be installed and operated by a small staff.

This method of structural testing is based on small vibrations whose amplitudes mainly depend on the wind intensity. Hence, there is a possibility that the structural properties inferred from these tests might considerably change during higher levels of vibration. In a recent study (Trifunac, 1970) a comparison was made of the results determined from wind and microtremor induced vibrations and the results of the vibration generator tests of the same building. The amplitudes of the wind excited vibrations were of the order of 100 times smaller than the steady state vibration amplitudes from the vibration generator tests. The frequencies determined from the ambient vibration tests were found to be about 4% higher than those from the vibration generator experiment. The mode shapes agreed closely.

Although several case studies are not sufficient to justify general conclusions, the results strongly suggest that testing based on microtremor and wind induced vibrations gives essentially the same results as would be obtained from the forced vibration experiments, in the linear range of excitation.

It should be pointed out here that many modern dynamic studies, although aimed at acquiring information which would assist in the design of earthquake resistant structures, are based on infinitesimal, linear theory of elasticity. Hence, the study of small vibrations can be used to check and improve various assumptions involved in constructing dynamical mathematical models of structures.

Theoretical studies of earthquake resistant structures will in the future tend to be increasingly more concerned with calculations based on elasto-plastic and other nonlinear force-deflection relationships. During these large, partially damaging motions, modes and natural periods of the structure will be different from those determined by linear theory or by experiments based on low-level forced vibration or on wind and microtremor-induced vibrations. However, even then the small amplitude experimental determinations of structural properties will be valuable, since they can serve as reference points for more complete calculations.

Only a small number of buildings has so far been tested by the ambient vibration measurement method and many more tests are needed. Vibration generator tests have been performed on various structures, including dams, atomic reactors and many buildings (e.g. Jennings and Kuroiwa, 1968). However, many more structures will have to be tested in the future, employing existing and developing techniques of measurement, before our knowledge of structural dynamics is based on sound foundations.

A SHORT DESCRIPTION OF THE BUILDING

The Union Bank Building* in the city of Los Angeles rises for 42 stories, 536 feet from the second basement level to the roof, with 39 stories, 496 feet, above the plaza level (Figure 1). It is located at Fifth and Figueroa Streets. The tower is of rectangular cross section, fourteen by seven bays or 196 feet by 98 feet (Figure 2). The typical story height, above the eleventh floor is 12' 1". Three levels of parking together with a plaza level 302 feet by 514 feet surround the lower four stories of the central tower.

The main entrance and lobby are on the plaza level. The second through 39th floors are occupied by the offices, the first and second basements and the street level are used for parking, storage, office services, rental area, truck loading and mechanical equipment. The air handling equipment occupies the 39th floor.

The structural steel frames are moment resistant for vertical and lateral loads for the full height of the tower. Shear walls are provided from the second basement level to the second floor. Typical floor construction consists of a lightweight concrete over steel beams at seven feet spacing. The structural engineers were Albert C. Martin and Associates of Los Angeles who were also associate architects for the project.

The tower is structurally separated from the parking structure by a joint allowing two inches of differential horizontal movement. Spread footings are continuous under the exterior columns of the tower and in the transverse direction under the shear core. Individual spread footings support interior columns.

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* The building, owned by the Connecticut General Life Insurance Company, derives its name from the principal tenant.

UNION BANK BUILDING LOS ANGELES

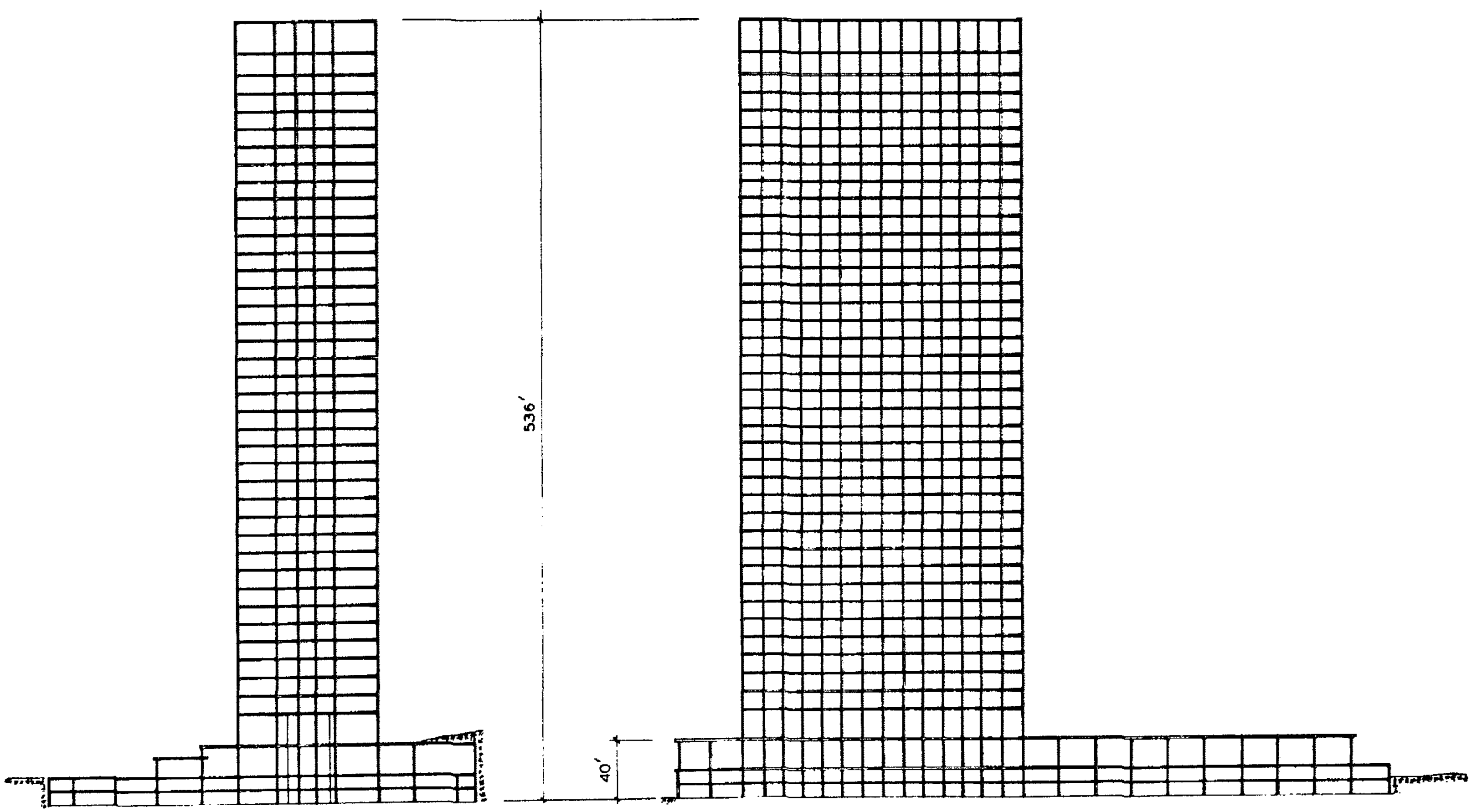
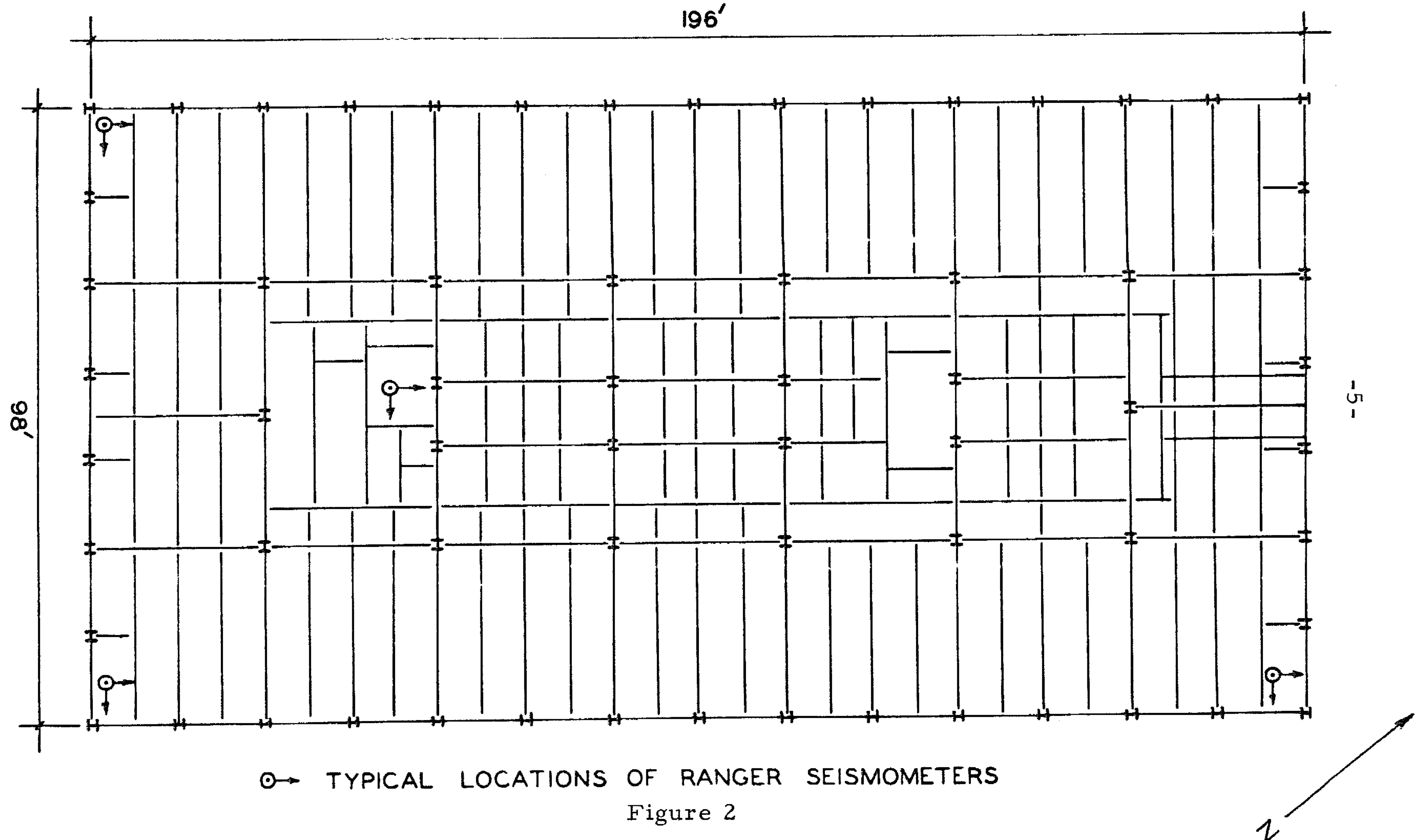


Figure 1

Simplified transverse and longitudinal sections of the Union Bank Building in Los Angeles.



⊙→ TYPICAL LOCATIONS OF RANGER SEISMOMETERS

Figure 2

Typical floor plan of the Union Bank Building in Los Angeles showing locations of ranger seismometers.

The wind loads for design were 30 psf. Design static seismic loads were about 50% greater than those required by the City of Los Angeles Building Code. The dynamic behavior of the structure for seismic loads was also investigated by computing the response for the El Centro earthquake, May 18, 1940 N-S component of the ground motion.

FIELD PROCEDURES

The instruments used during the field measurements consisted of four Teledyne Ranger seismometers, a four chanel signal conditioner and a magnetic tape recorder. A more detailed description of similar measuring equipment is given in a previous report (Trifunac 1970). The equipment was owned and operated by the Teledyne Company, under contract to the California Institute of Technology.

The first step in the field procedures was to record vibrations with all four seismometers oriented in the same direction and placed side by side on the 39th floor. This is done in order to calibrate dynamically four simultaneous outputs. It is not necessary to adjust the four instruments so that they give exactly the same amplitudes, nor is it necessary to find the actual amplitudes of the recorded motions. The modes of building vibrations can be determined from the ratios of the instrument outputs.

Following the calibration run, two seismometers were left on the 39th floor, one oriented NS (seismometer Number 3) and one EW (seismometer Number 4). The other two seismometers were moved to the 36th floor. Seismometer Number 1 was oriented NS and seismometer Number 2 EW. A five minute recording was made and was referred to as Run 2. During the following, Runs 3, 4, ... , 15, seismometers Numbers 1 and 2 were successively moved to the lower floors. For each run an interval of five minutes of vibration was recorded. Table 1 shows the location and the orientation of each seismometer during the measurements.

To determine torsional vibrations Runs 16 and 17 were performed. During Run 17 all four seismometers were on the 39th floor in the NE

TABLE 1 Seismometer Location by Run Number

	Floor			
	Seismometer No. 1	Seismometer No. 2	Seismometer No. 3	Seismometer No. 4
Run No.	NS	EW	NS	EW
2	36	36	39	39
3	33	33	39	39
4	30	30	39	39
5	27	27	39	39
6	24	24	39	39
7	21	21	39	39
8	18	18	39	39
9	15	15	39	39
10	12	12	39	39
11	9	9	39	39
12	6	6	39	39
13	3	3	39	39
14	1	1	39	39
15	S.L	S.L.	39	39
16	21*	21*	39*	39*
17	39**	39**	39***	39***

Legend	S.L.	Street Level	
	*	In SE Corner	
	**	In SW Corner	see Figure 2
	***	In NE Corner	

and SW corners of the tower (Figure 2). During Run 16 all seismometers were in the SE corner, two on the 39th and two on the 21st floors. The instrument locations and orientations are shown in Figure 2.

It is easily seen that the Fourier amplitude spectra of the sum of the EW or NS vibration records from Run 17 emphasizes translational frequencies and practically cancels torsional frequencies. On the other hand, the Fourier amplitude spectrum of the difference of the two EW or NS records from the same Run 17 emphasizes the torsional motions and cancels translational motions.

The recorded quantity during all measurements was the relative velocity of the seismometer mass which has a natural frequency close to 1 cps. When adjusted to 70% of critical damping the instrument response is nearly flat for frequencies greater than about 1 cps and has a 12 db per octave slope for frequencies smaller than about 1 cps. As a result, recorded vibrations with frequencies less than one cps are partly reduced in size. Such properties of the transducer are advantageously used to filter the large low-frequency oscillations that usually result from the fundamental modes of vibration. This partial filtering of the long-period oscillations facilitates the data recording and processing and permits greater emphasis of the higher frequencies during the recording.

DATA PROCESSING

The demodulated signals from the FM magnetic tape were played back through a band pass filter transmitting frequencies from 0.1 to 10 cps. This filter has a constant gain between 0.1 and 10 cps and falls off with 24 db per octave slope outside of this interval. The purpose of this filtering is to eliminate high frequency noise which is almost always present during the wind and microtremor vibration measurements. This noise, often caused by the electronics of the recording system or various installations in the building and its surroundings, is normally composed of frequencies much higher than those associated with the vibration modes under study. To provide for the more economical data analysis by employing fewer digitized points the noise is reduced either by digital filtering (Trifunac, 1970) after the analog to digital conversion, or by analog filtering prior to the analog to digital conversion.

The filtered signal was digitized by taking 20 equally spaced points per second . This corresponds to the Nydquist frequency $f_N = 10$ cps. For each run (Table 1), 4096 data points were generated corresponding to approximately 205 seconds. The Fourier amplitude spectrum was computed by using Cooley-Tukey algorithm (Cooley and Tukey, 1965). For 4096 data points this algorithm gives 2048 spectral estimates and 2048 phase angles. In order to statistically improve their accuracy the obtained spectral estimates were averaged by eight and decimated by four. This gave 512 spectral estimates equally distributed between 0 and 10 cps. The frequency resolution is then 10/512 or about 0.02 cps. For each run (Table 1) four Fourier amplitude and phase spectra are computed corresponding to each seismometer record. Typical spectra

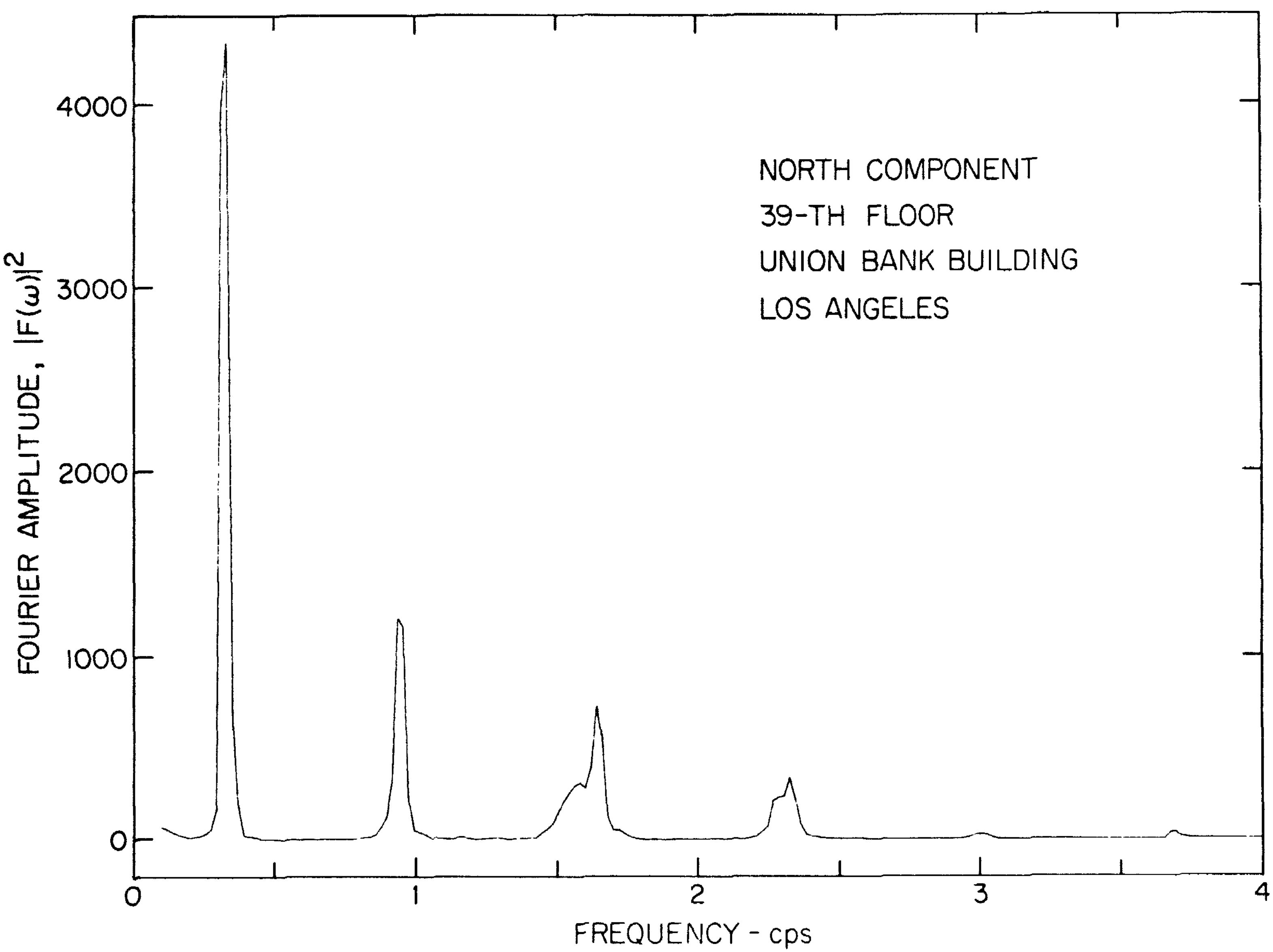


Figure 3

The square of the Fourier amplitude spectrum of the north component of the velocity recorded on the 39th floor. The scale for the square of the Fourier amplitudes is arbitrary.

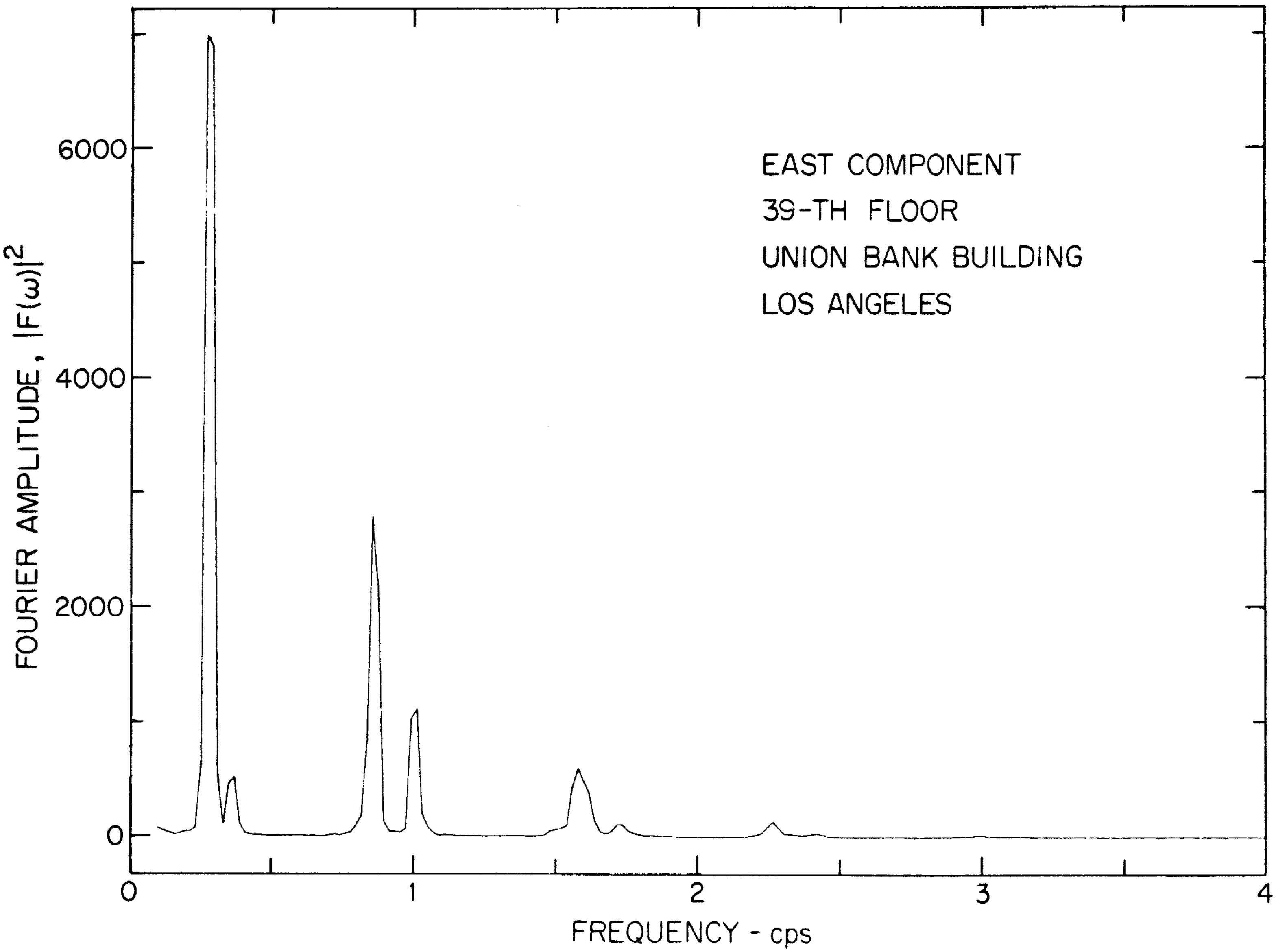


Figure 4

The square of the Fourier amplitude spectrum of the east component of the velocity recorded on the 39th floor. The scale for the square of the Fourier amplitudes is arbitrary.

from vibrations recorded in NS and EW directions on the 39th floor are given in Figures 3 and 4. To emphasize the characteristic frequencies the square of the Fourier amplitude $|F(\omega)|^2$ is plotted in Figures 3 and 4 rather than the usual Fourier Amplitude spectrum $|F(\omega)|$. As is seen in Figure 4 the EW component has double peaks. The position of the central south stairwell (Figure 2) where the instruments were located for Runs 2 to 15 allowed the torsional vibrations to be recorded on the EW instrument components. This is the reason for double peaks in all spectra for the EW direction. The torsional Run 17 indicated that the higher frequency peak in each group represents the torsional modes.

The details of the present data processing procedures differ from those in our previous study (Trifunac, 1970) in that analog instead of the digital smoothing is used. Also, considerably longer record intervals are analyzed here, leading to higher resolution of the unsmoothed spectral estimates.

The choice of the particular steps in the data processing will for each case depend on the quality and type of the data, available equipment for analysis and the use of the processed information.

FREQUENCIES AND MODES OF VIBRATION

In order to determine the natural frequencies of vibration, spectra from Runs 2 to 15 were averaged. The average of the spectra of all EW records on the 39th floor gave the EW and torsional frequencies and the average spectra from all NS records gave NS translational frequencies. As may be seen in Figures 3 and 4 the relative excitation of the higher modes decreases with increasing frequency to become indistinguishable from the noise level at about sixth or seventh natural frequency.

The frequencies for the first seven EW and torsional modes and for the six NS modes are given in Table 2. Figure 5 and Table 2 give the ratios of the i^{th} higher frequency to the corresponding fundamental frequency. These ratios are helpful in that they indicate a type of overall structural response. As may be seen the ratios for the NS translational frequencies are very close to the ratios for the uniform shear beam. The EW vibrations indicate some contribution of bending effects.

The procedure for determining mode shapes is to divide the spectral amplitude of the response on a given floor by the spectrum amplitude of the simultaneously recorded response on the top floor. Repeating this procedure for all floors where the measurements were made, the mode amplitudes, apart from a multiplicative constant, can be determined. One common procedure is to normalize the modes so that the biggest value becomes unity. Although the modes are determined only by a few discrete points which are subject to all possible experimental errors, one may pass a polynomial through those points to approximate the continuous mode shape. For a statistically more precise determination of modal amplitudes and for better resolution of the mode shapes, more experimental

TABLE 2

Natural frequencies, frequency ratios f_i/f_1 and damping.

Mode Number	EW			NS			TORSION		
	Frequency f_i-cps	Ratio f_i/f_1	Damping % critical	Frequency f_i-cps	Ratio f_i/f_1	Damping % critical	Frequency f_i-cps	Ratio f_i/f_1	Damping % critical
1	.283	1.00	1.5±0.1	.322	1.00	1.7±0.3	.361	1.00	1.8±0.3
2	.858	3.01	1.5±0.2	.935	2.90	1.5±0.1	1.004	2.78	1.5±0.2
3	1.579	5.57	1.5±0.2	1.639	5.08	1.8±0.2	1.733	4.81	1.7±0.1
4	2.251	7.95	1.5±0.2	2.310	7.17	2.0±0.1	2.409	6.68	1.4±0.2
5	2.972	10.50	3.0±0.5	2.982	9.27	2.0±0.2	3.090	8.55	1.5±0.2
6	3.695	13.05	2.0±0.4	3.692	11.45	0.5±0.1	~3.860	10.70	--
7	4.550	16.07	1.9±0.3	--		--	4.620	12.80	--

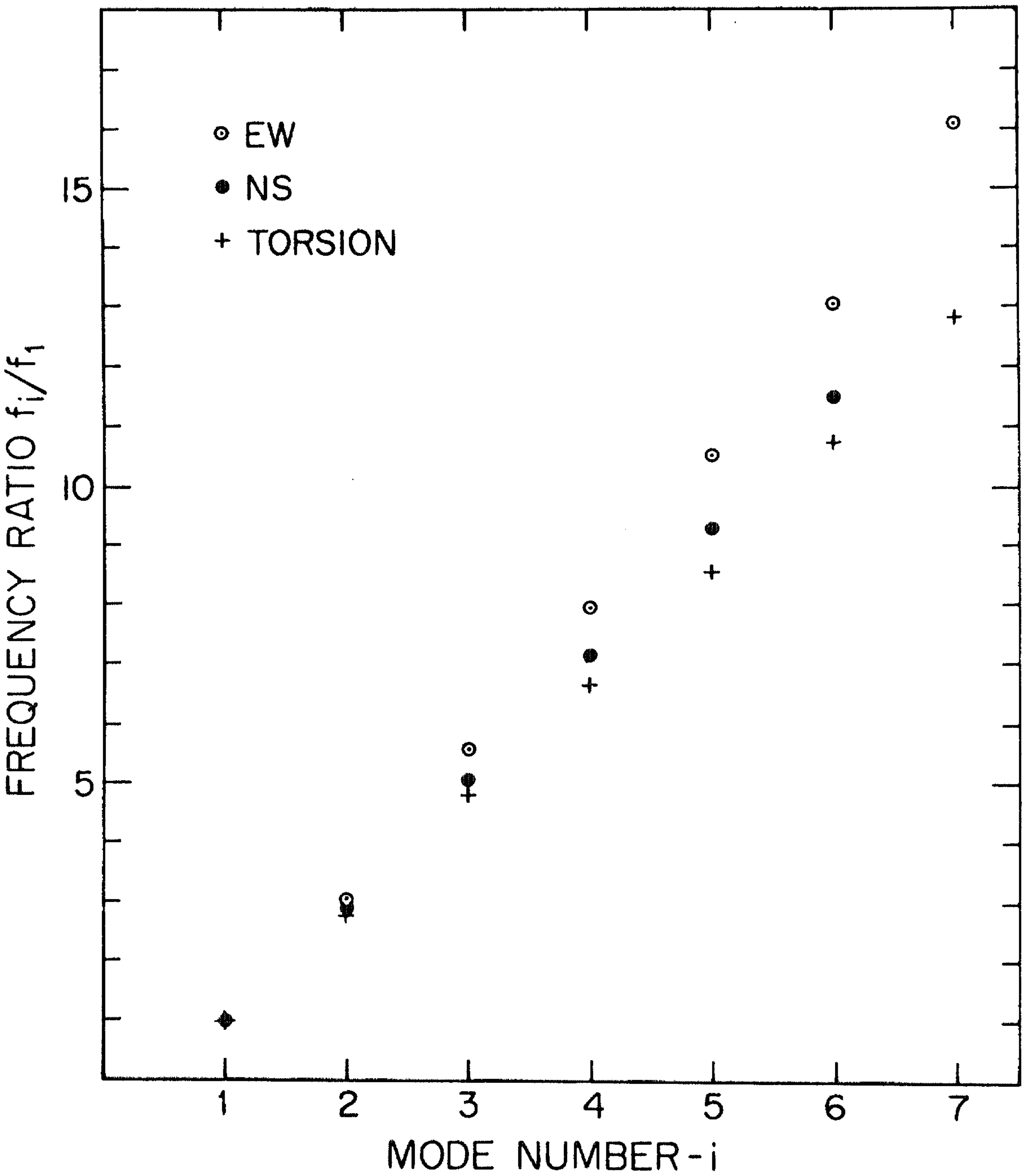


Figure 5

The ratios of the higher and the fundamental frequencies for the six modes.

points would be required. A dozen to fifteen points is close to the minimum if the first five or six modes are to be determined.

Modes determined from the ratio of the Fourier amplitude spectra are plotted in Figures 6a to 8e. The modal amplitudes are also given in Tables 3 and 4 for the EW and NS directions, and in Table 5 for the torsional vibrations. No special measurements were made to determine accurately the center of rotation of the various floors.

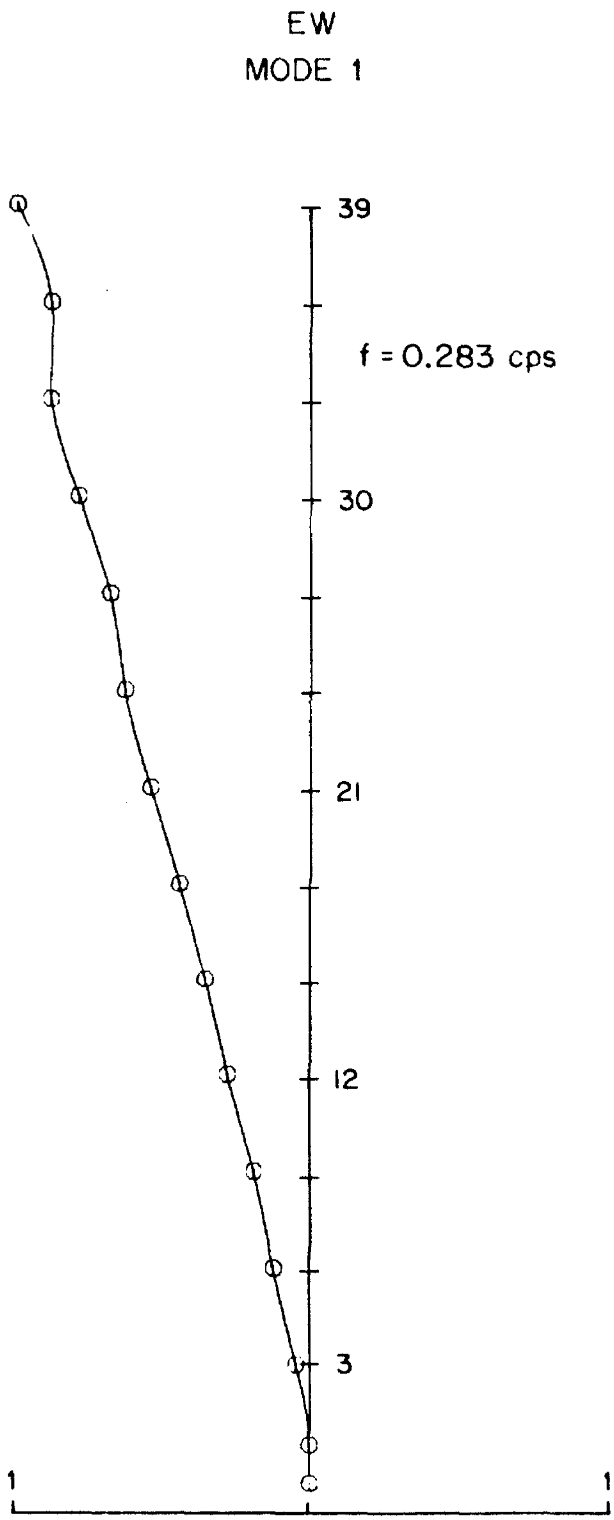


Figure 6a
First EW Mode

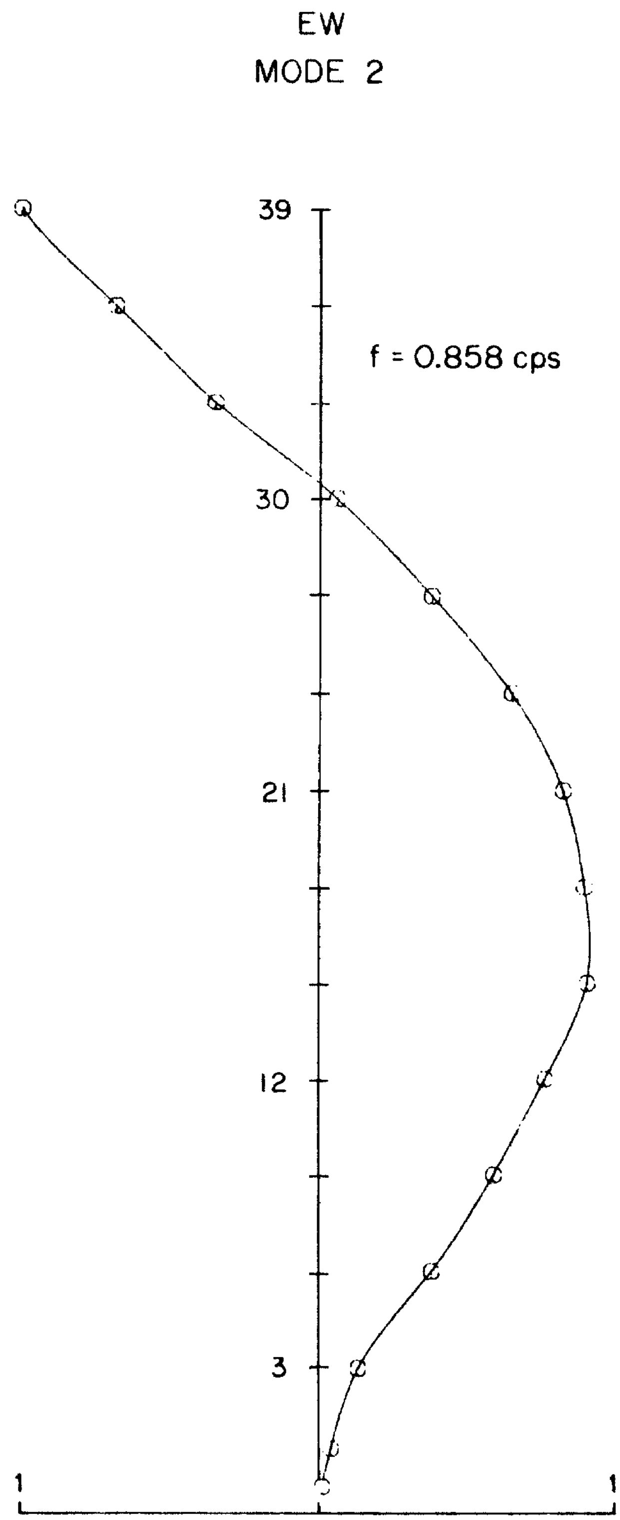


Figure 6b
Second EW Mode

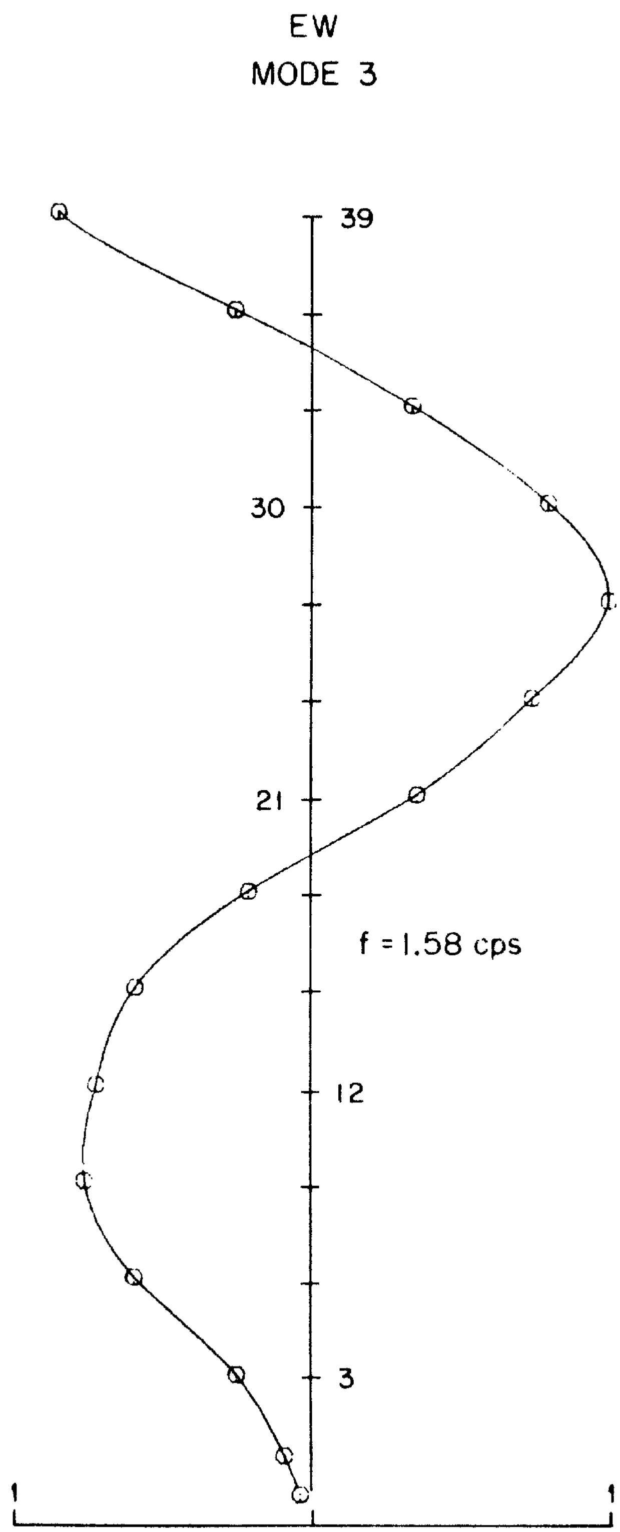


Figure 6c
Third EW Mode

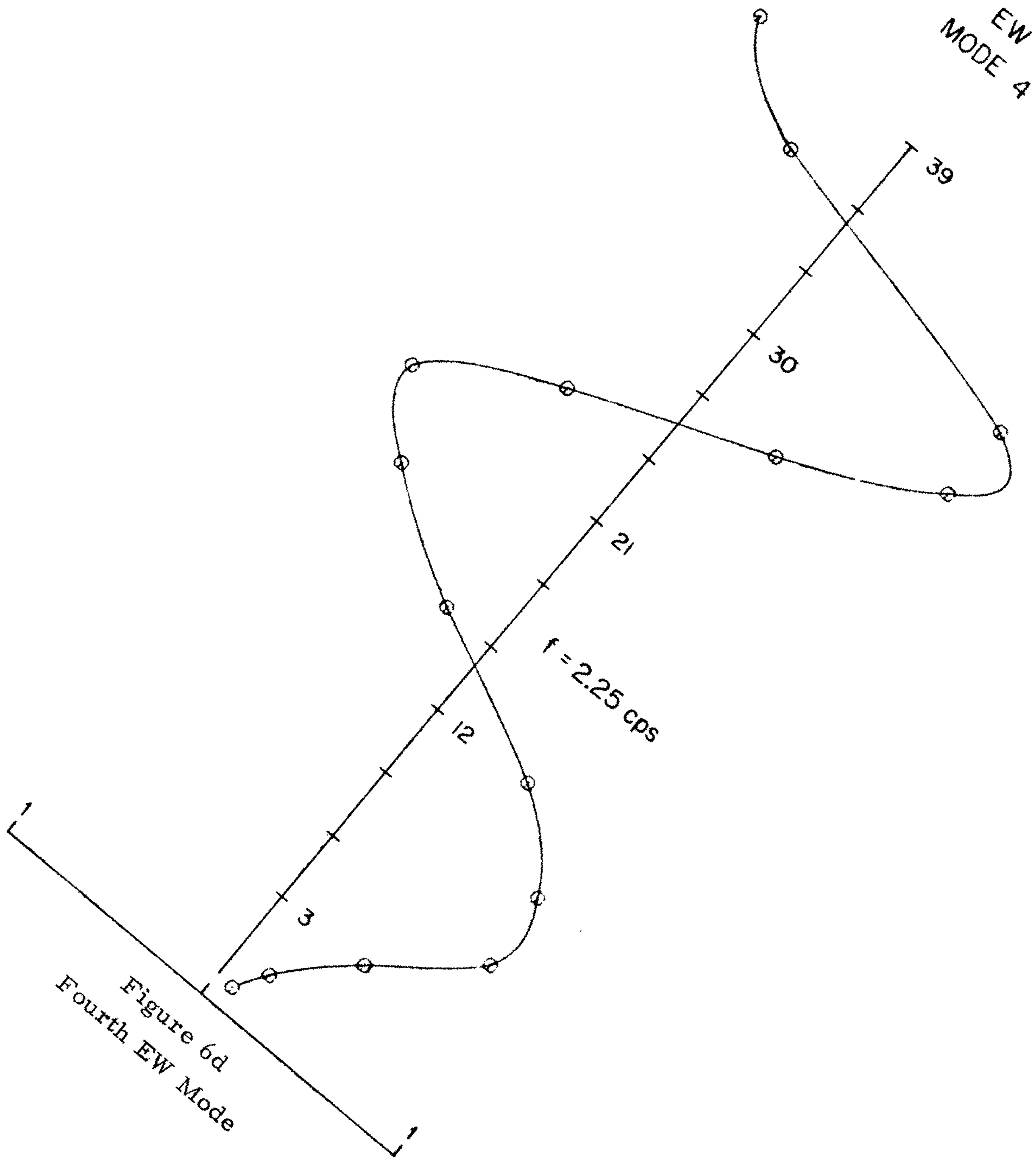


Figure 6d
Fourth EW Mode

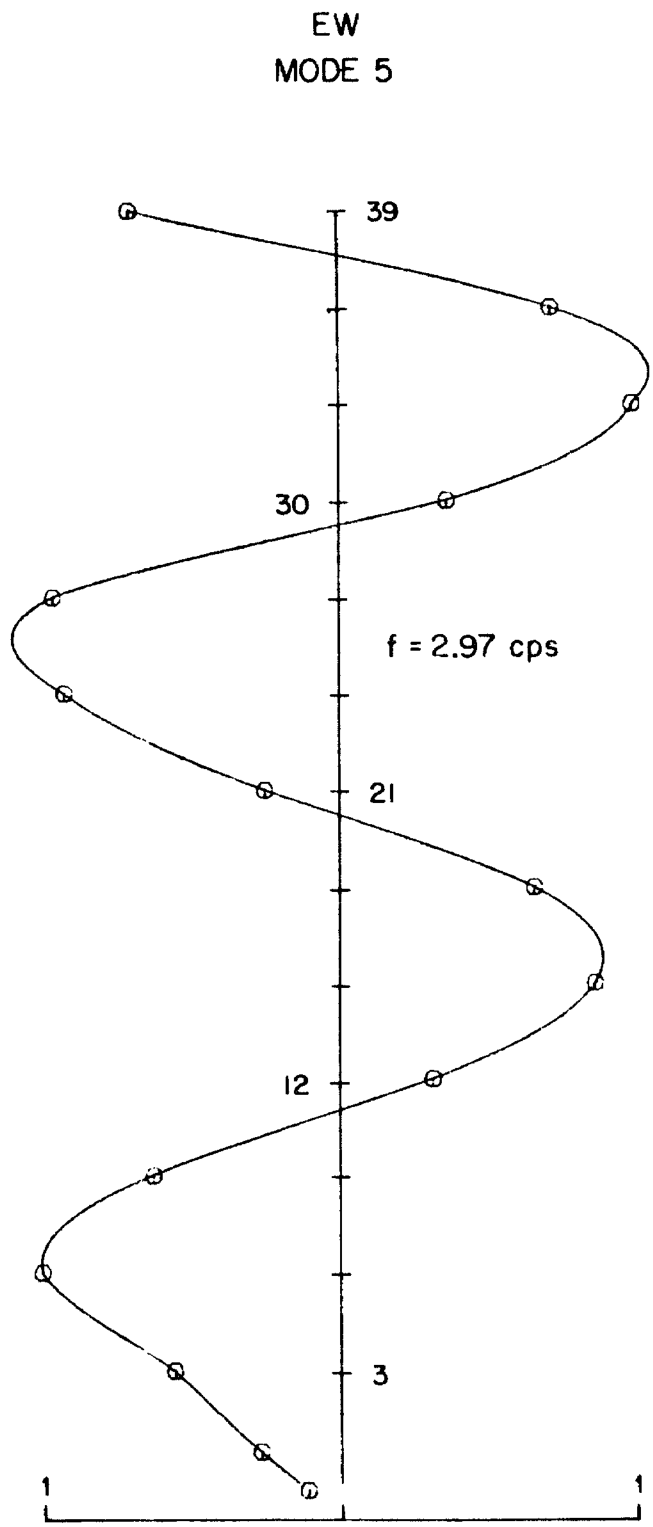


Figure 6e
Fifth EW Mode

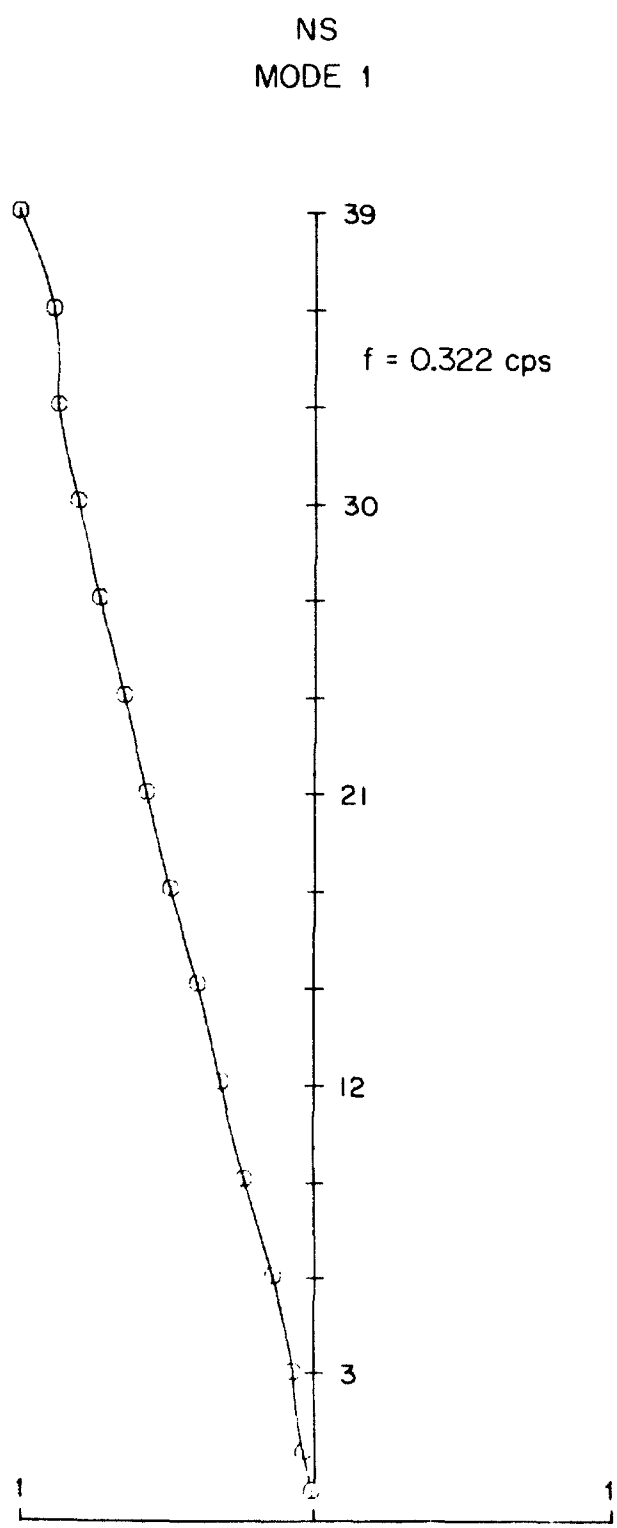


Figure 7a
First NS Mode

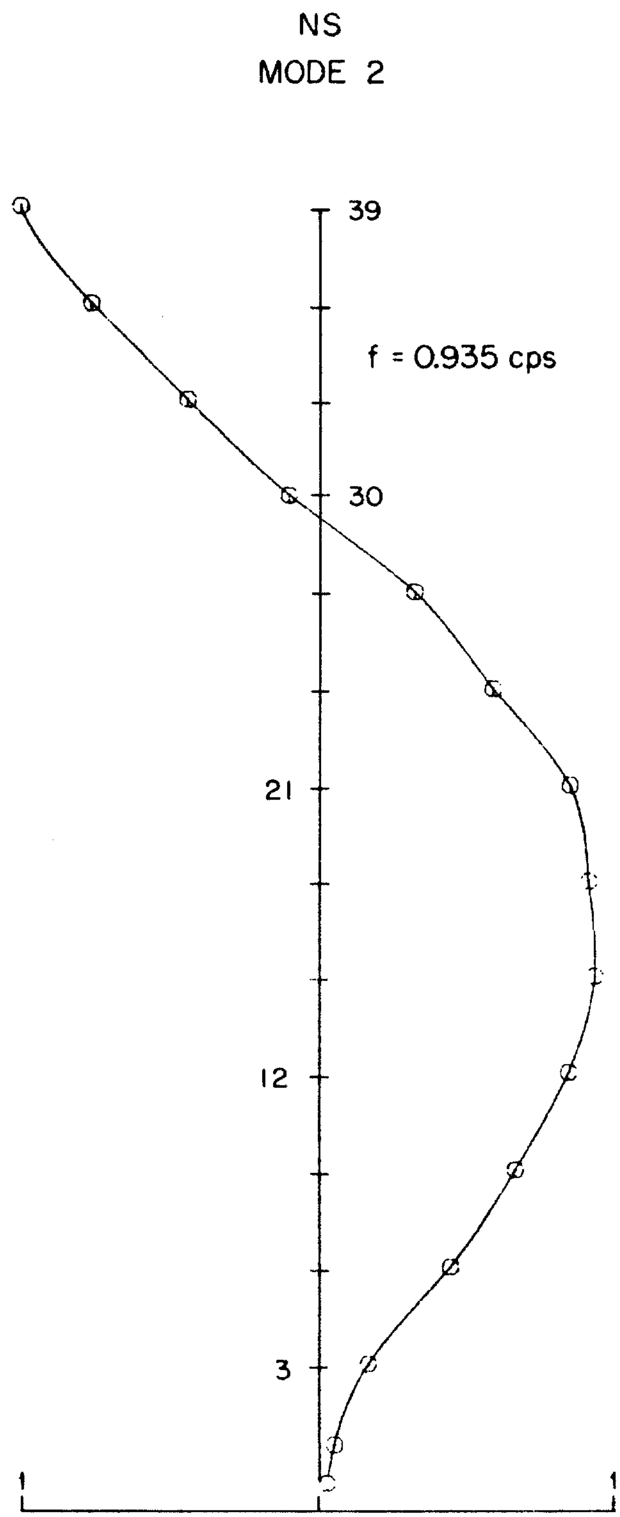


Figure 7b

Second NS Mode

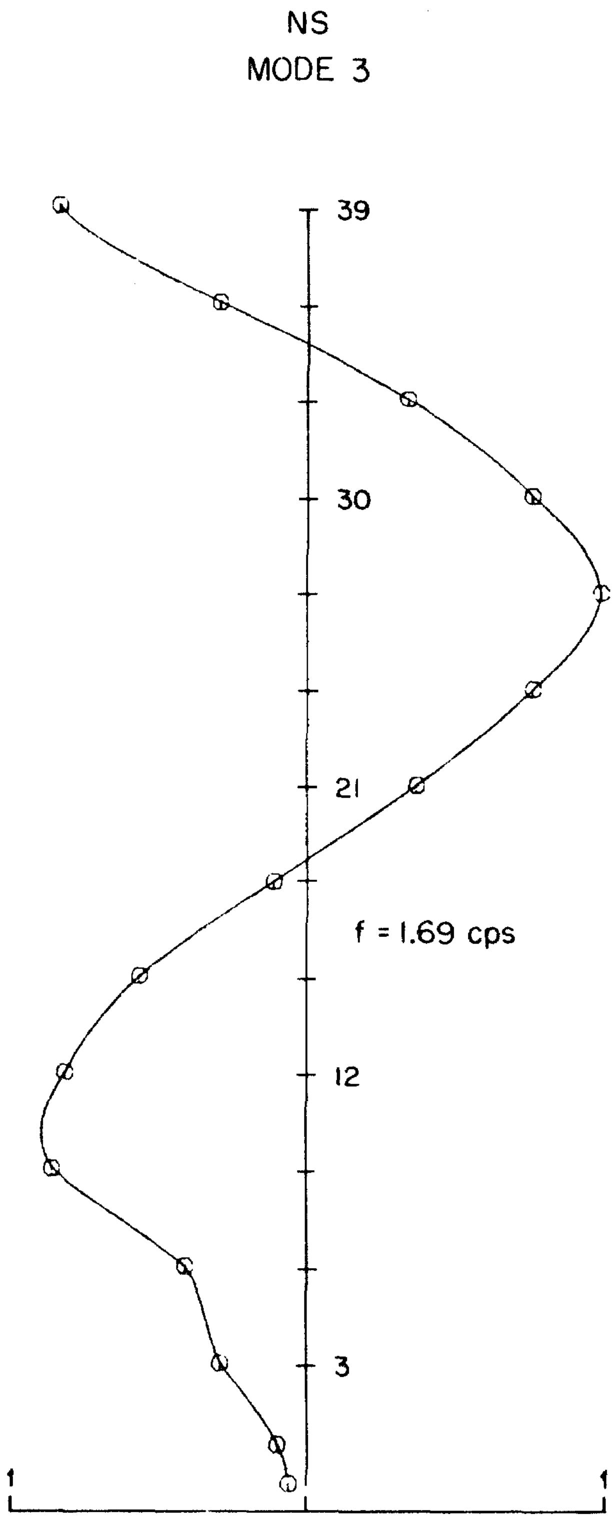


Figure 7c
Third NS Mode

NS
MODE 4

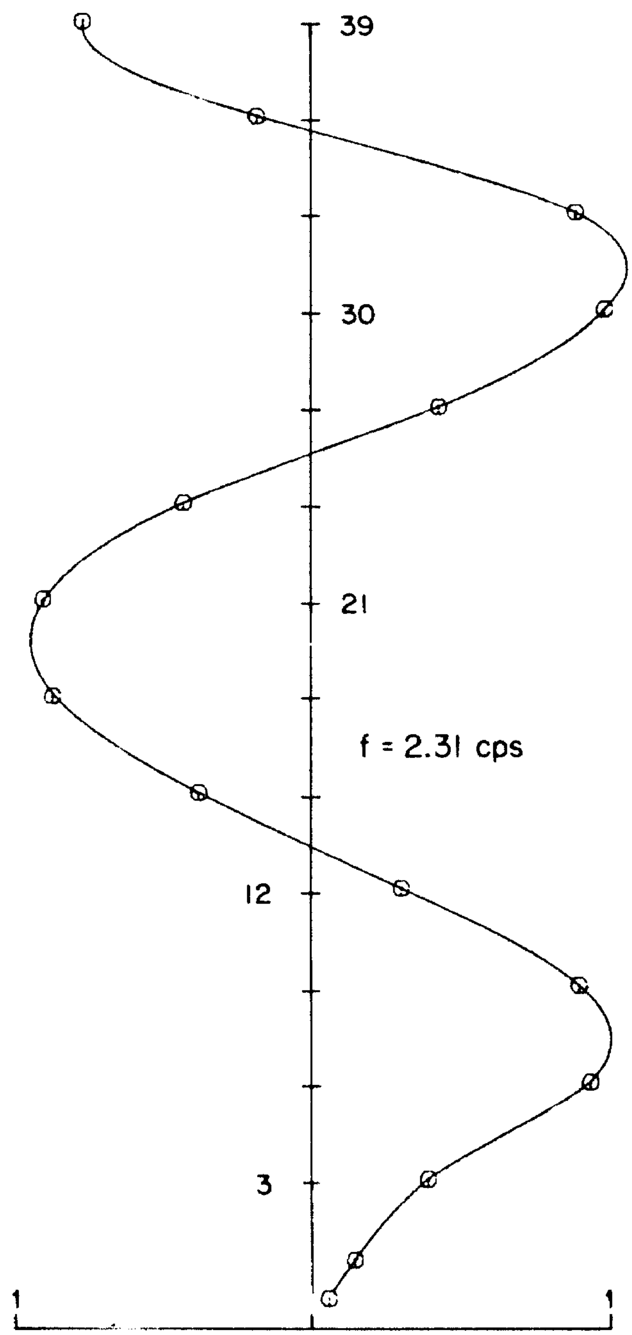


Figure 7d
Fourth NS Mode

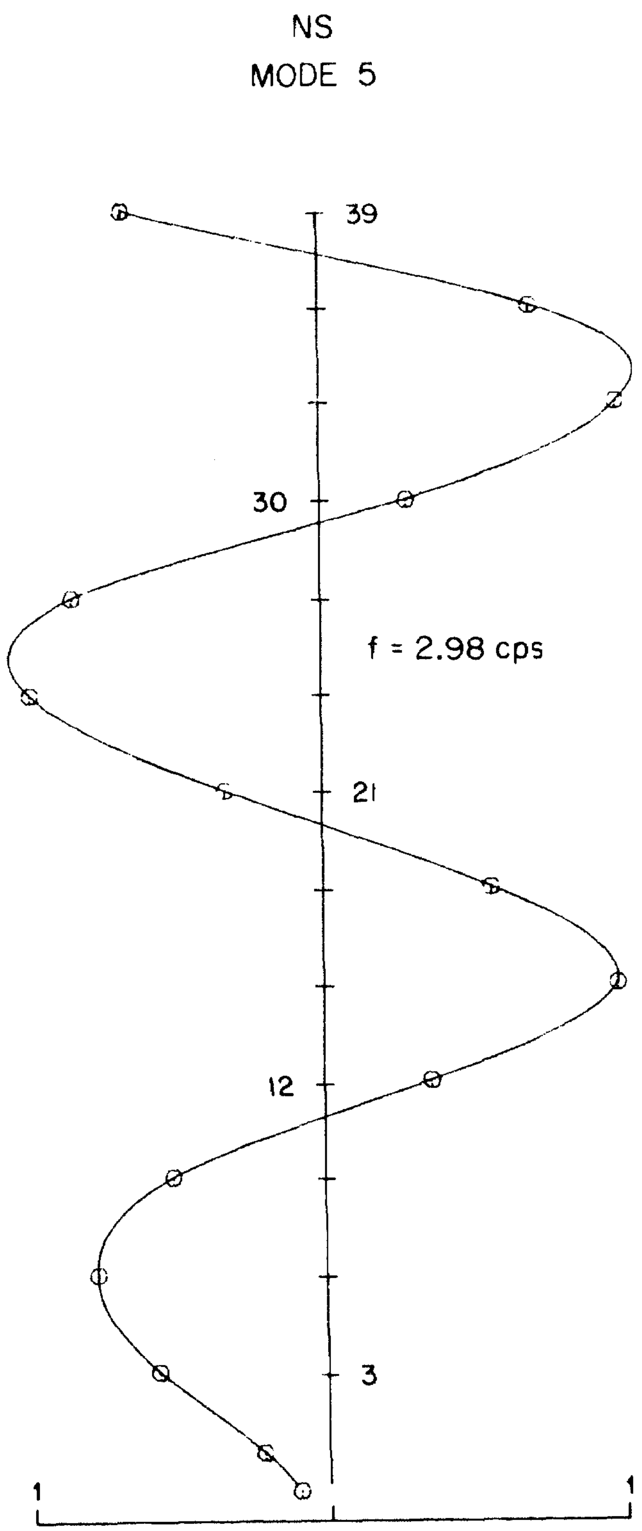


Figure 7e
Fifth NS Mode

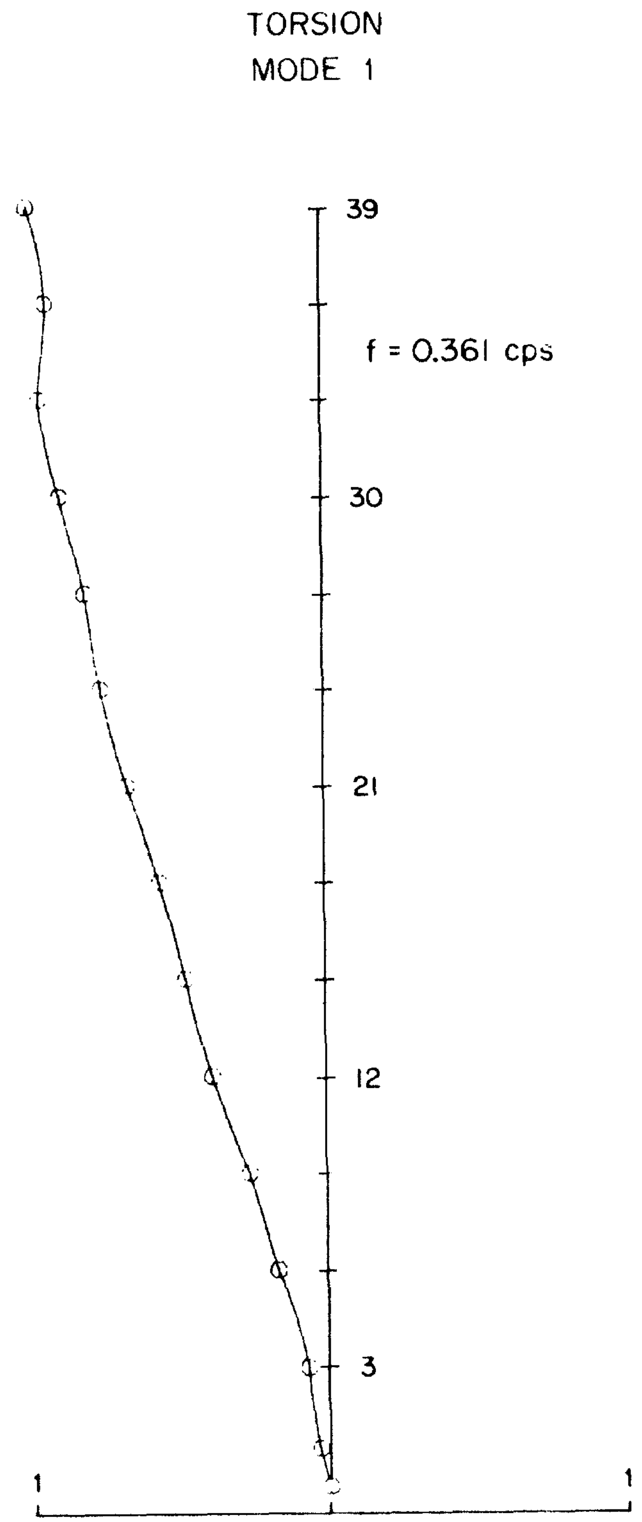


Figure 8a
First Torsional Mode

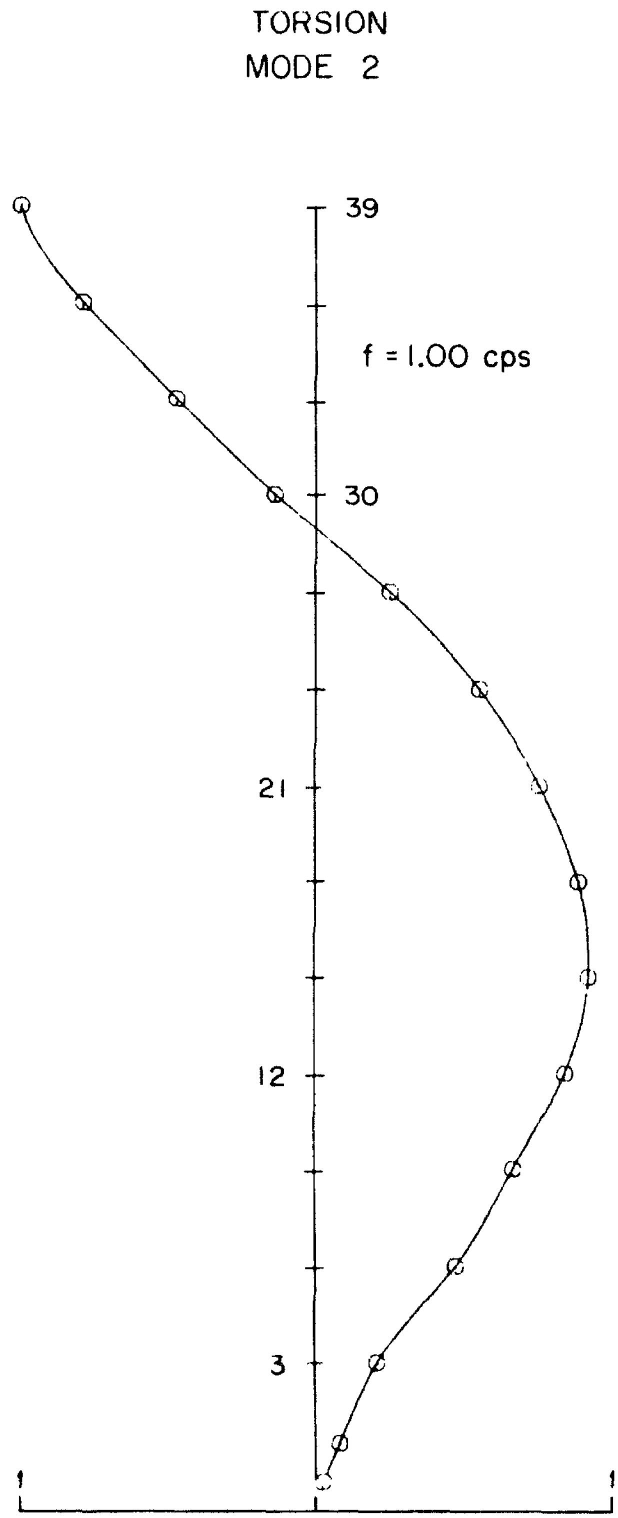


Figure 8b
Second Torsional Mode

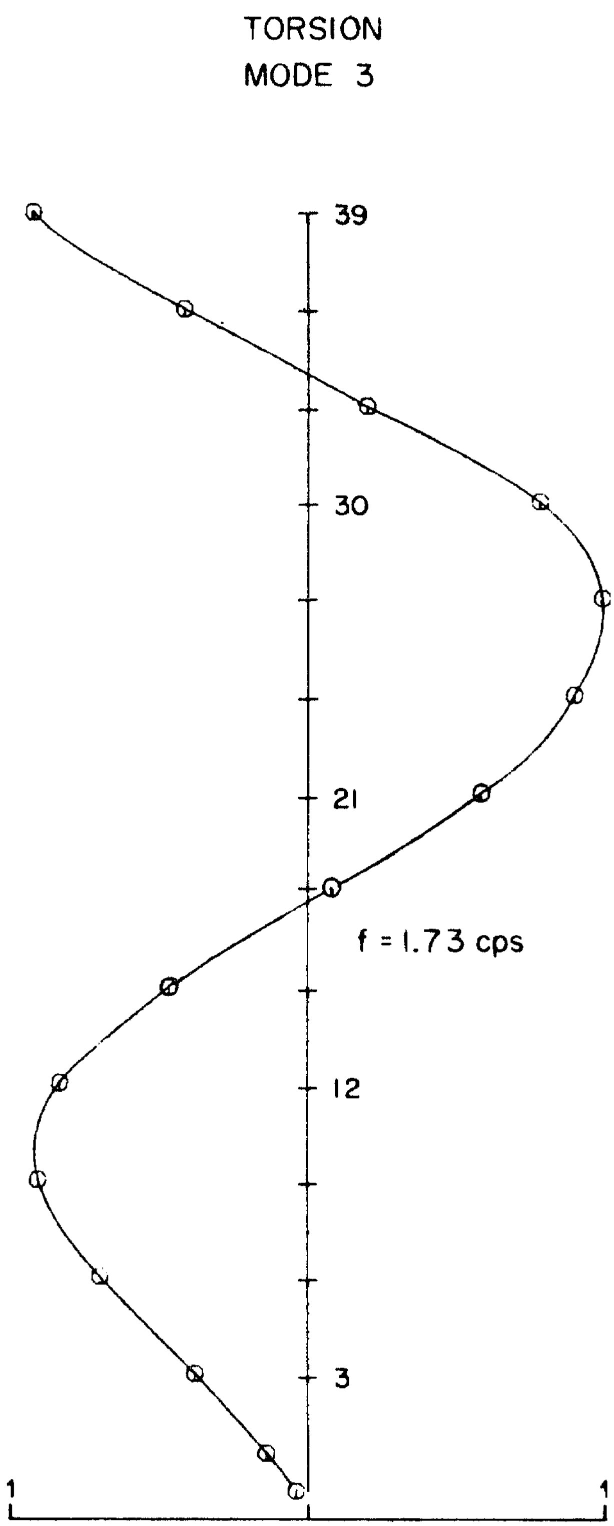


Figure 8c
Third Torsional Mode

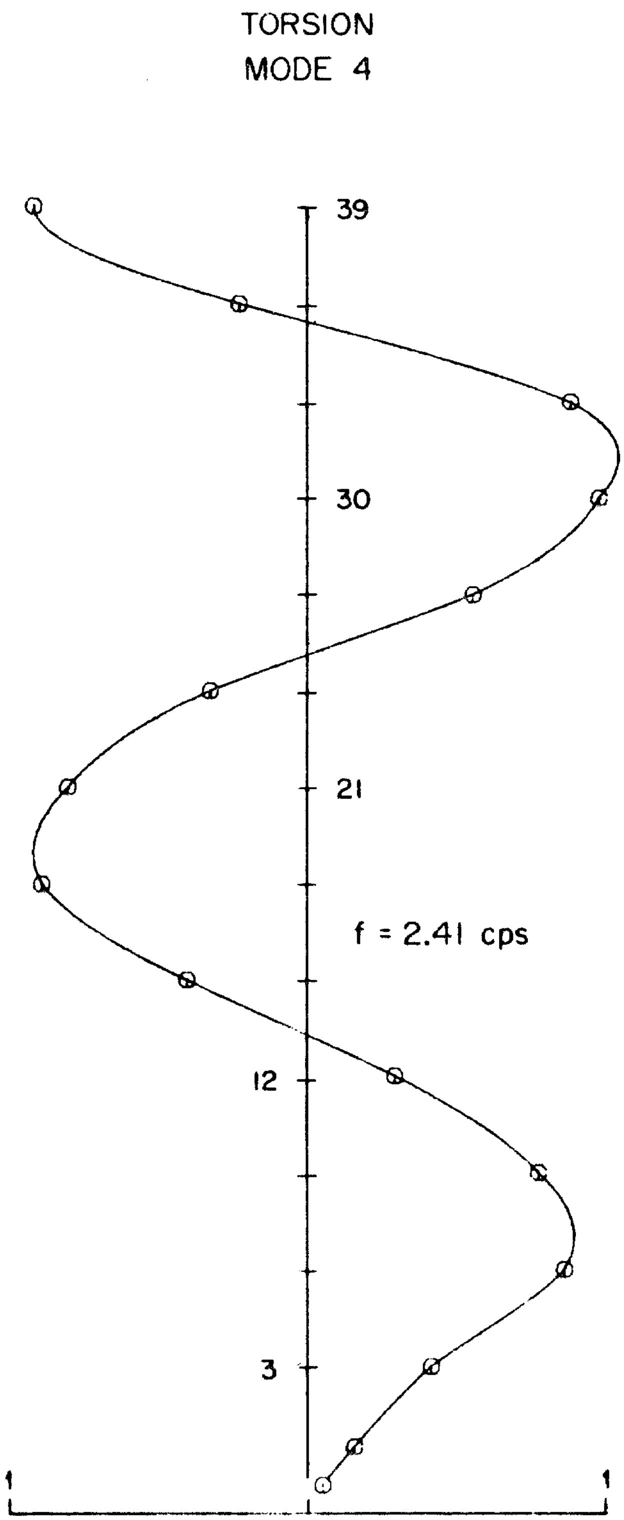


Figure 8d
Fourth Torsional Mode

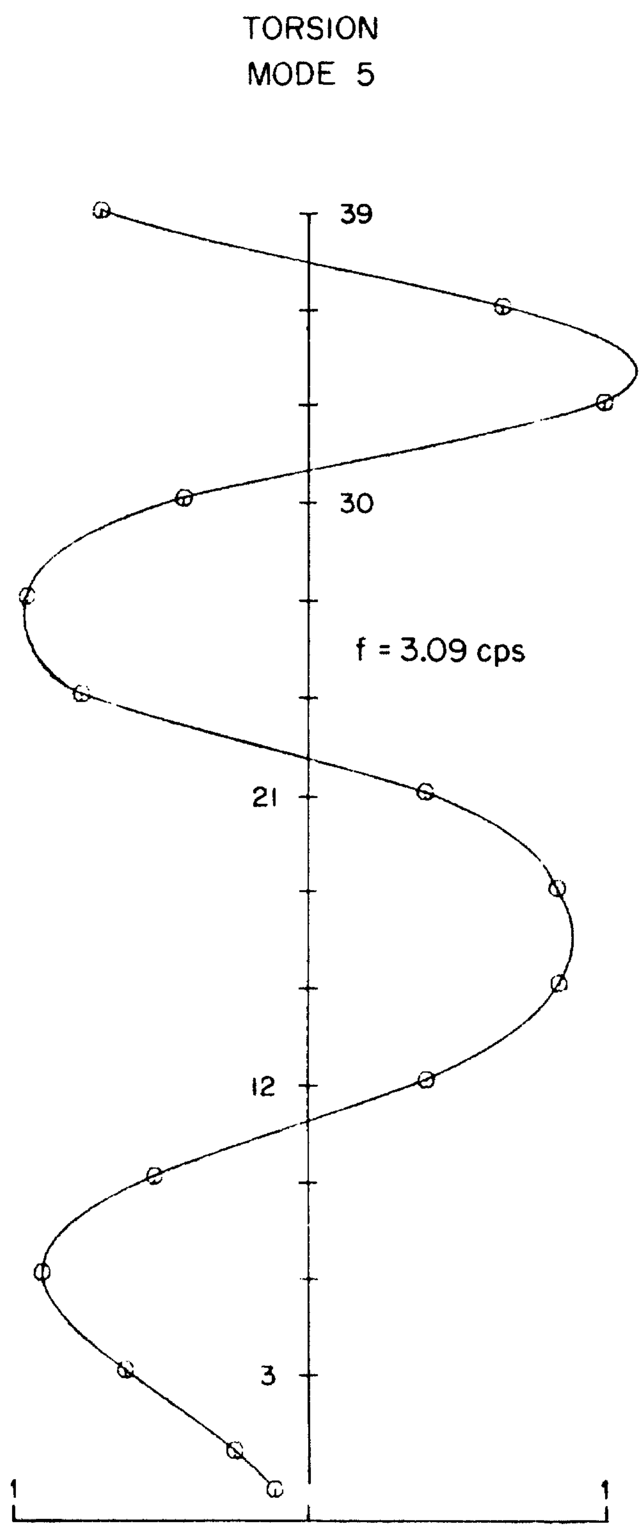


Figure 8e
Fifth Torsional Mode

TABLE 3

Floor	EW MODES				
	1	2	3	4	5
39	1.00	1.00	0.86	0.80	0.70
36	0.89	0.68	0.26	0.36	-0.72
33	0.88	0.35	-0.33	-1.00	-1.00
30	0.79	-0.07	-0.80	-1.00	-0.37
27	0.68	-0.39	-1.00	-0.38	0.96
24	0.63	-0.66	-0.74	0.43	0.92
21	0.54	-0.84	-0.35	0.96	0.24
18	0.44	-0.91	0.21	0.74	-0.67
15	0.36	-0.92	0.60	0.24	-0.87
12	0.28	-0.78	0.73	-0.46	-0.32
9	0.19	-0.61	0.76	-0.78	0.62
6	0.12	-0.40	0.60	-0.81	1.00
3	0.05	-0.15	0.26	-0.42	0.55
1	~0	-0.06	0.09	-0.16	0.26
S. L.	~0	-0.03	0.04	-0.08	0.10

TABLE 4

Floor	NS MODES				
	1	2	3	4	5
39	1.00	1.00	0.83	0.76	0.66
36	0.88	0.76	0.29	0.17	-0.71
33	0.87	0.44	-0.35	-0.90	-1.00
30	0.80	0.09	-0.77	-1.00	-0.29
27	0.72	-0.33	-1.00	-0.44	0.84
24	0.64	-0.59	-0.77	0.42	0.98
21	0.56	-0.86	-0.38	0.89	0.33
18	0.48	-0.92	0.10	0.85	-0.57
15	0.39	-0.94	0.55	0.37	-0.99
12	0.31	-0.85	0.80	-0.31	-0.36
9	0.23	-0.67	0.85	-0.91	0.51
6	0.13	-0.45	0.40	-0.95	0.77
3	0.06	-0.17	0.28	-0.40	0.57
1	0.03	-0.06	0.09	-0.15	0.22
S. L.	~0	-0.03	0.05	-0.06	0.10

TABLE 5

Floor	TORSIONAL MODES				
	1	2	3	4	5
39	1.00	1.00	0.91	0.91	0.70
36	0.94	0.79	0.40	0.21	-0.66
33	0.96	0.47	-0.21	-0.90	-1.00
30	0.89	0.14	-0.79	-1.00	0.42
27	0.81	-0.25	-1.00	-0.57	0.95
24	0.76	-0.55	-0.90	0.31	0.76
21	0.67	-0.75	-0.59	0.79	-0.40
18	0.56	-0.89	-0.09	0.88	-0.84
15	0.47	-0.92	0.46	0.39	-0.85
12	0.39	-0.84	0.83	-0.31	-0.41
9	0.26	-0.67	0.90	-0.80	0.51
6	0.17	-0.48	0.69	-0.89	0.89
3	0.07	-0.21	0.37	-0.43	0.61
1	0.03	-0.08	0.13	-0.17	0.24
S. L.	~ 0	-0.03	0.04	-0.07	0.11

DAMPING

The equivalent viscous damping during the ambient vibrations may be estimated by using the half-power point method. This way of determining the damping is based on the assumption that the wind and microtremor excitations are nearly stationary during the experimental measurements.

When the NS, EW and torsional frequencies are nearly the same and when optimum location of the seismometers in the field is not achieved, damping computed by the half-power method may be too large (Trifunac 1970). The present case can serve as an example of the optimum location of seismometers to accomplish the best separation of the peaks in the Fourier spectra of the recorded vibrations. The location of the southern stairwell (Figure 2) on the axis of symmetry but sufficiently off the center of the building so that torsional components of the vibrations can be measured, appears to be nearly ideal. From the typical spectra of Figures 3 and 4, it is clear that one would like to choose a recording site on one of the two axis of symmetry for which the frequencies are as far apart as possible. To accomplish this, it is necessary to know at least the fundamental frequencies in NS, EW and torsion before the main measurements are taken. These frequencies which can be found from a simple trial test indicate which axis is preferable for location of the seismometers. Final decisions may be governed by field considerations, in particular by the location of the stairwells and problems of access.

The equivalent viscous damping factors determined for most of the natural frequencies are given in Table 2. The damping for the EW and torsional frequencies was estimated from the average spectra of all EW records on the 39th floor and the damping for the NS natural frequencies from the average of the spectra of all NS records on the same floor.

CONCLUSIONS

The ambient vibration tests of the Union Bank Building in the downtown Los Angeles area resulted in the determination of the first seven frequencies and first five mode shapes of the translational and torsional vibrations. These frequencies and mode shapes are based on small amplitude vibrations and hence indicate the structural behavior in the range of linear response.

At the vibration levels of this test, no obvious trend is present in the damping values given in Table 2. For this particular structure it seems that the assumption of damping, independent of frequency, is preferable to more complex behavior, as, for example, explained by either stiffness or mass proportional damping.

The accuracy of estimating the equivalent viscous damping depends, among other things, on the degree to which the translational and torsional vibrations can be separated. This case study could serve as an example of the successful field separation which was made possible by the convenient stairwell location on the longitudinal axis of the building.

The overall simplicity of the dynamic properties of the structure is an important feature of the present test. The regularity of the frequency spacing, the resemblance of the modes to those of simple systems and the relatively constant damping lend encouragement to efforts to model tall building structures by simple systems (Jennings, 1969). These simple systems can be used to determine approximate earthquake loadings for design, in preference to building codes which may not be directly applicable, and to understand and interpret the earthquake response of the structures, as recorded by strong-motion instruments.

ACKNOWLEDGMENTS

The ambient vibration measurements in the Union Bank Building were made on 17 March, 1968 by the Teledyne Company under the supervision of Mr. V. R. McLamore. Portions of the data reduction and processing were also done by the same company.

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